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Radó

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(54) **METHOD AND DEVICE OF CALCULATING AIRCRAFT BRAKING FRICTION AND OTHER RELATING LANDING PERFORMANCE PARAMETERS BASED ON THE DATA RECEIVED FROM AIRCRAFT'S ON BOARD FLIGHT DATA MANAGEMENT SYSTEM**

(58) **Field of Classification Search** 244/1 R, 244/100 R, 110 A, 110 R, 111; 303/126, 303/177, 150; 701/70, 78, 83, 80
See application file for complete search history.

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This patent is subject to a terminal disclaimer.

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(Continued)

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Primary Examiner — Benjamin P Lee

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(65) **Prior Publication Data**

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(57) **ABSTRACT**

This invention relates to a method and apparatus for the calculation of aircraft braking friction and other relating landing parameters, including but not limited to aircraft braking action, aircraft takeoff distance, aircraft landing distance, runway surface conditions and runway surface friction based on the data collected by and available in the aircraft Flight Data Recorder (FDR) or other flight data management system, for example, the Quick Access Recorder (QAR), to provide all involved personnel in the ground operations of an airport and airline operations, including but not limited to aircraft pilots, airline operation officers and airline managers as well as airport operators, managers and maintenance crews, with the most accurate and most recent information on the true aircraft landing performance parameters to help better and more accurate safety and economical decision making.

Related U.S. Application Data

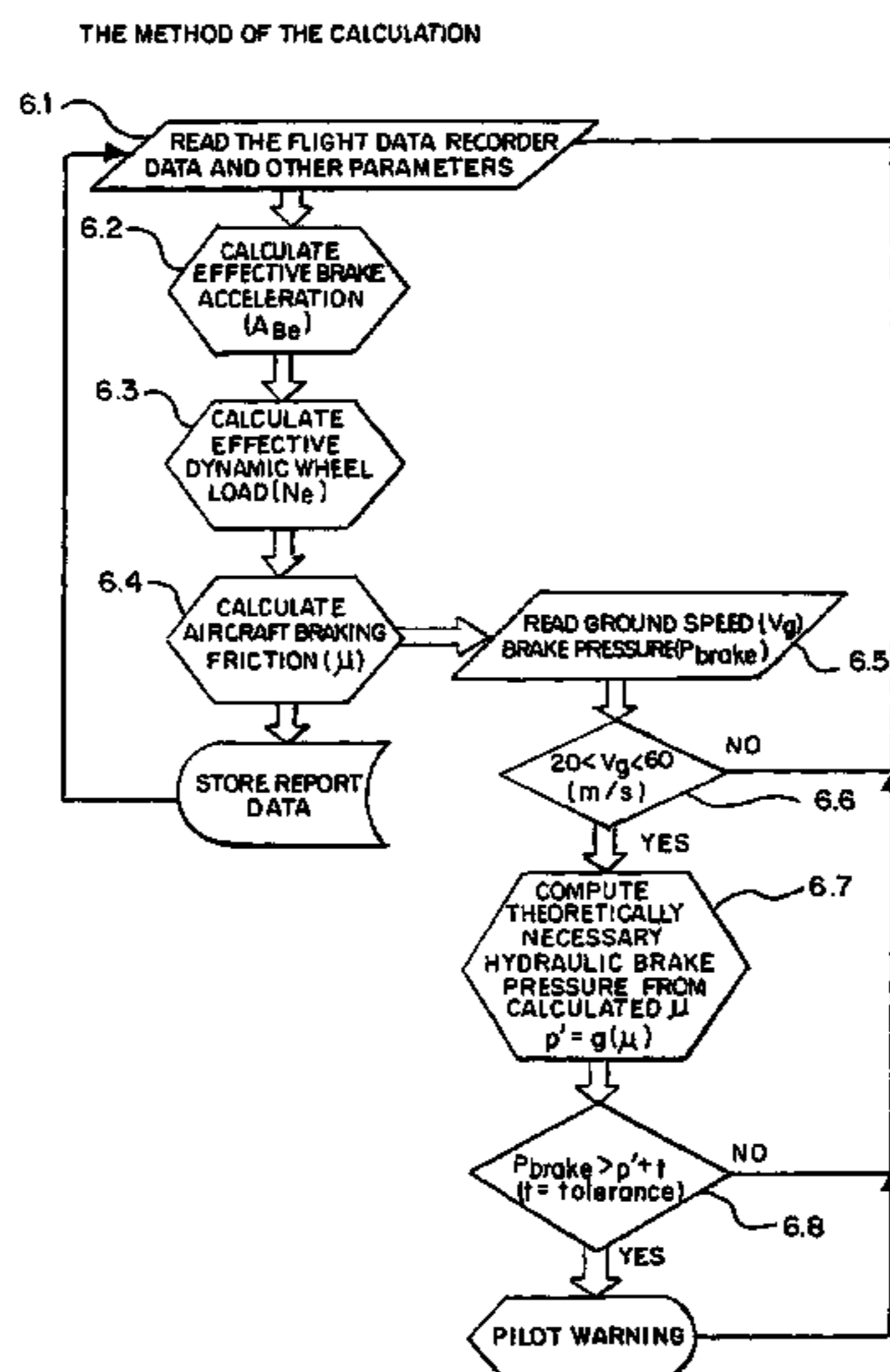
(63) Continuation of application No. 13/374,757, filed on Jan. 11, 2012, now Pat. No. 8,244,444, which is a continuation of application No. 12/802,065, filed on May 28, 2010, now Pat. No. 8,121,771, which is a continuation of application No. 11/352,984, filed on Feb. 13, 2006, now Pat. No. 7,797, 095.

(60) Provisional application No. 60/654,914, filed on Feb. 23, 2005.

(51) **Int. Cl.**
B64C 25/42 (2006.01)

(52) **U.S. Cl.** 701/80; 303/191; 244/111; 244/1 R

20 Claims, 6 Drawing Sheets



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FIG.1

FLIGHT DATA RECORDER SCHEMATIC

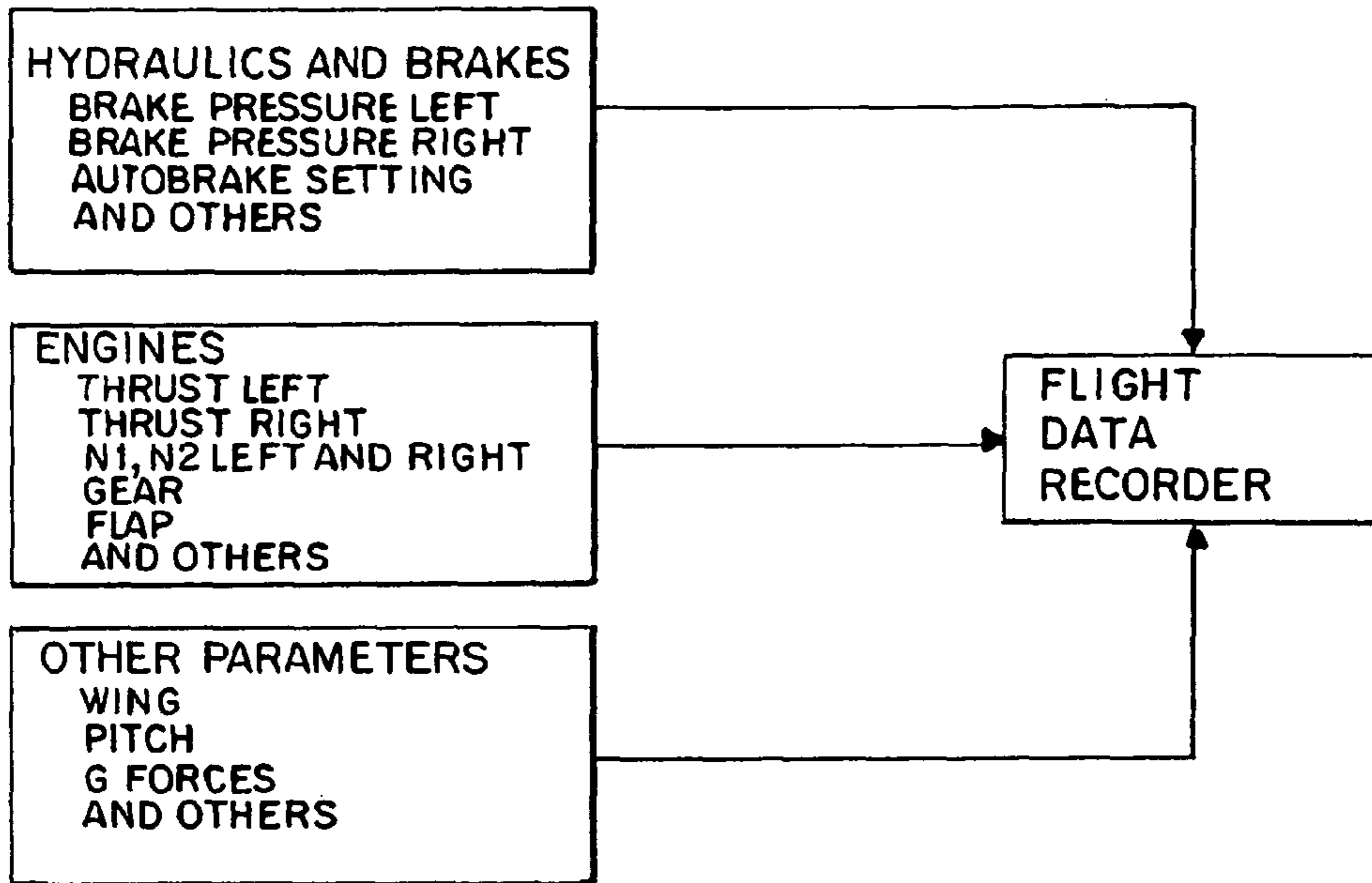


FIG.2

EXAMPLE PRESSURE ALTITUDE(FT)VERSUS TIME(S)DATA FROM THE FLIGHT DATA RECORDER

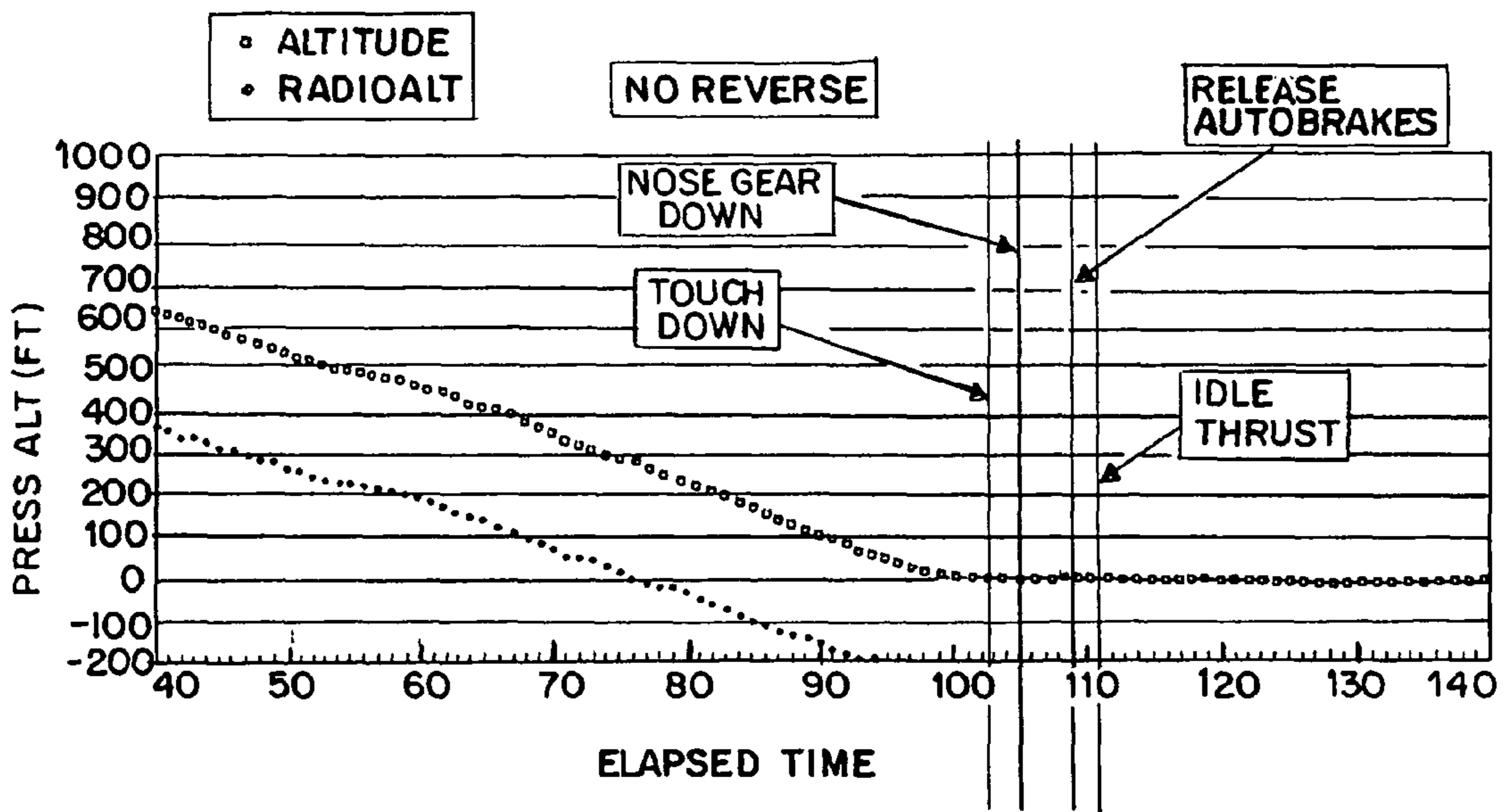


FIG. 3

EXAMPLE BRAKE PRESSURE(PSI)VERSUS TIME(S)DATA FROM THE FLIGHT DATA RECORDER DATA

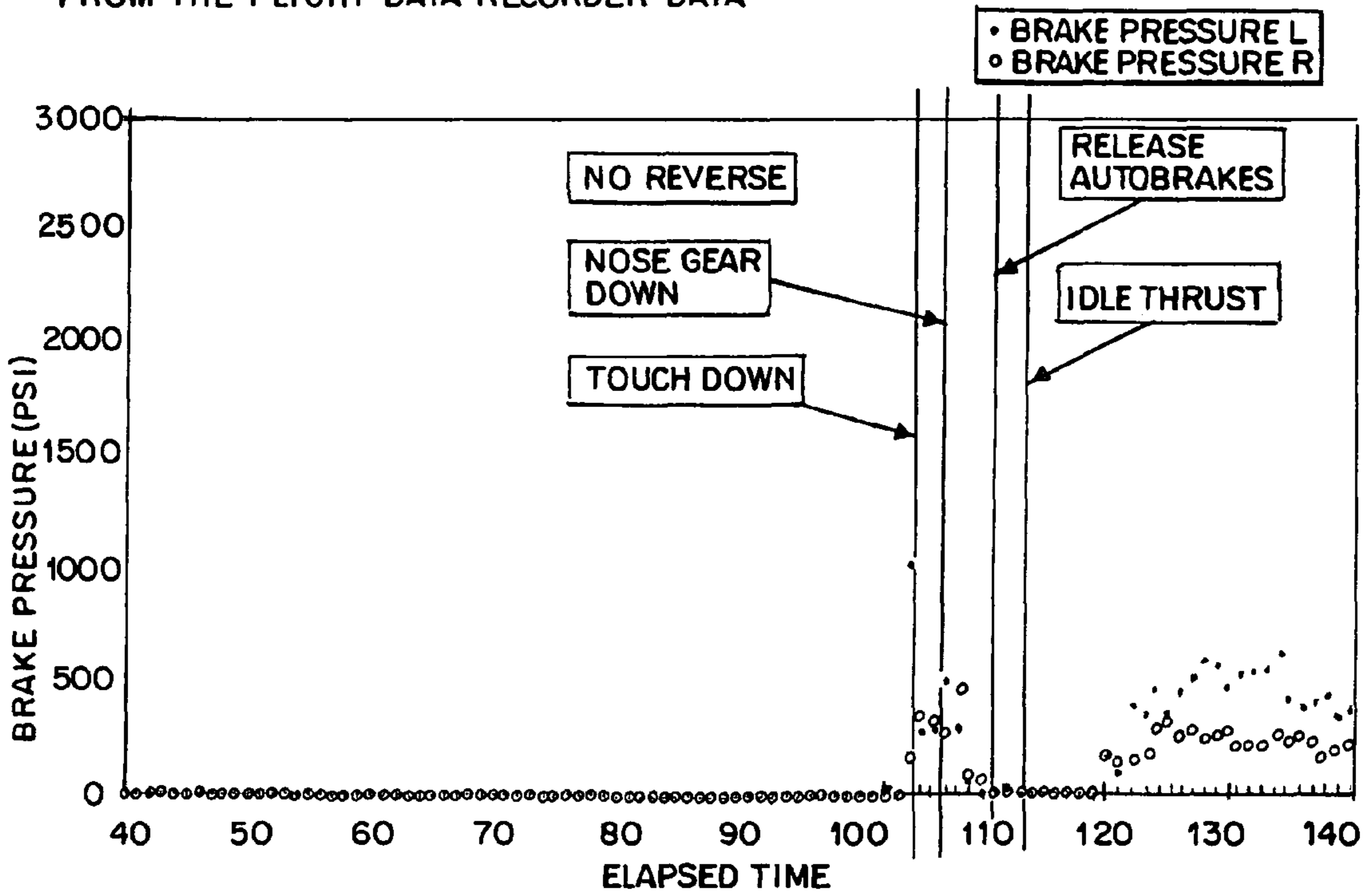


FIG. 4

EXAMPLE AUTOBRAKE SETTING VERSUS TIME(S) DATA FROM THE FLIGHT DATA RECORDER DATA

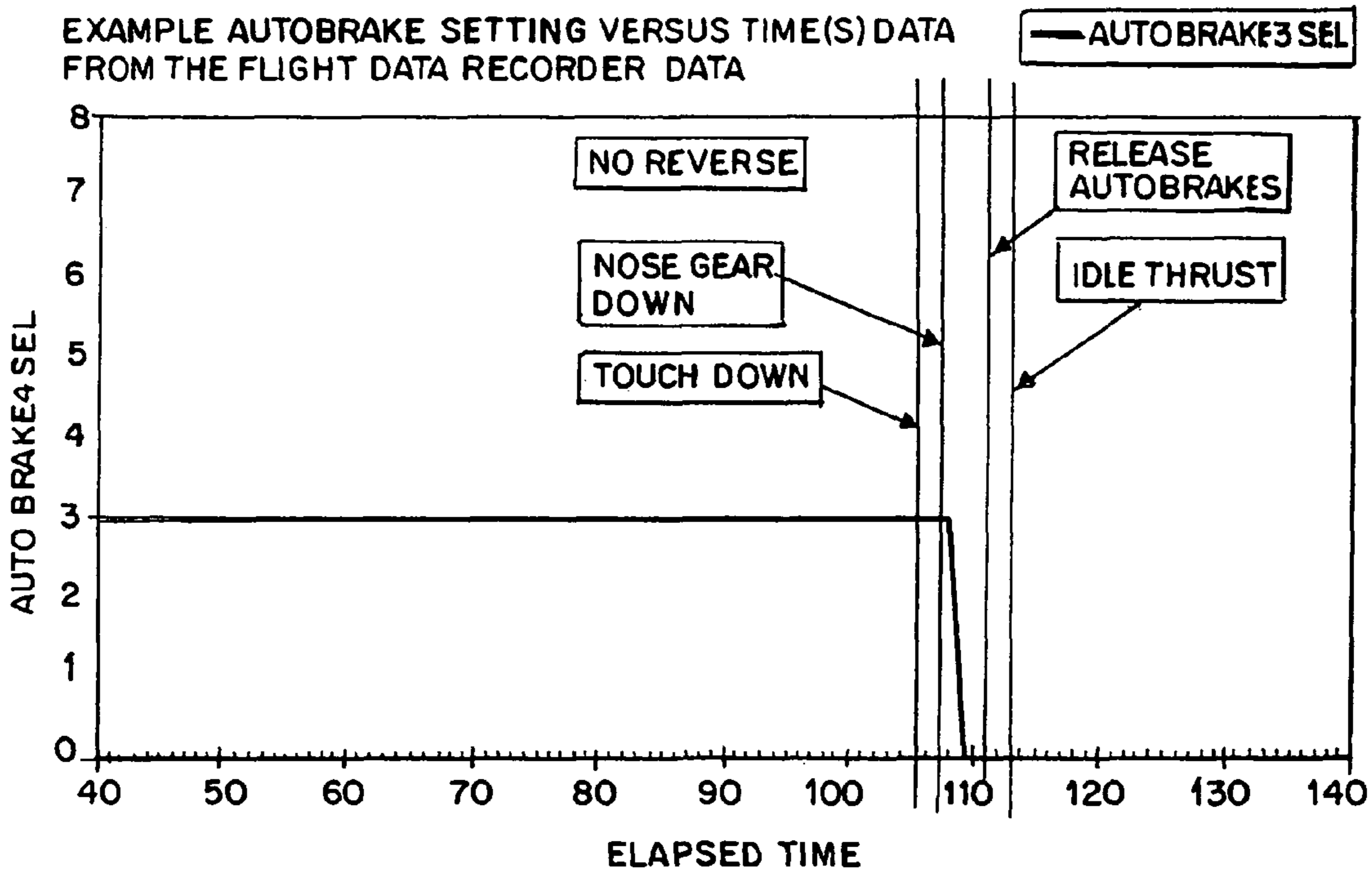


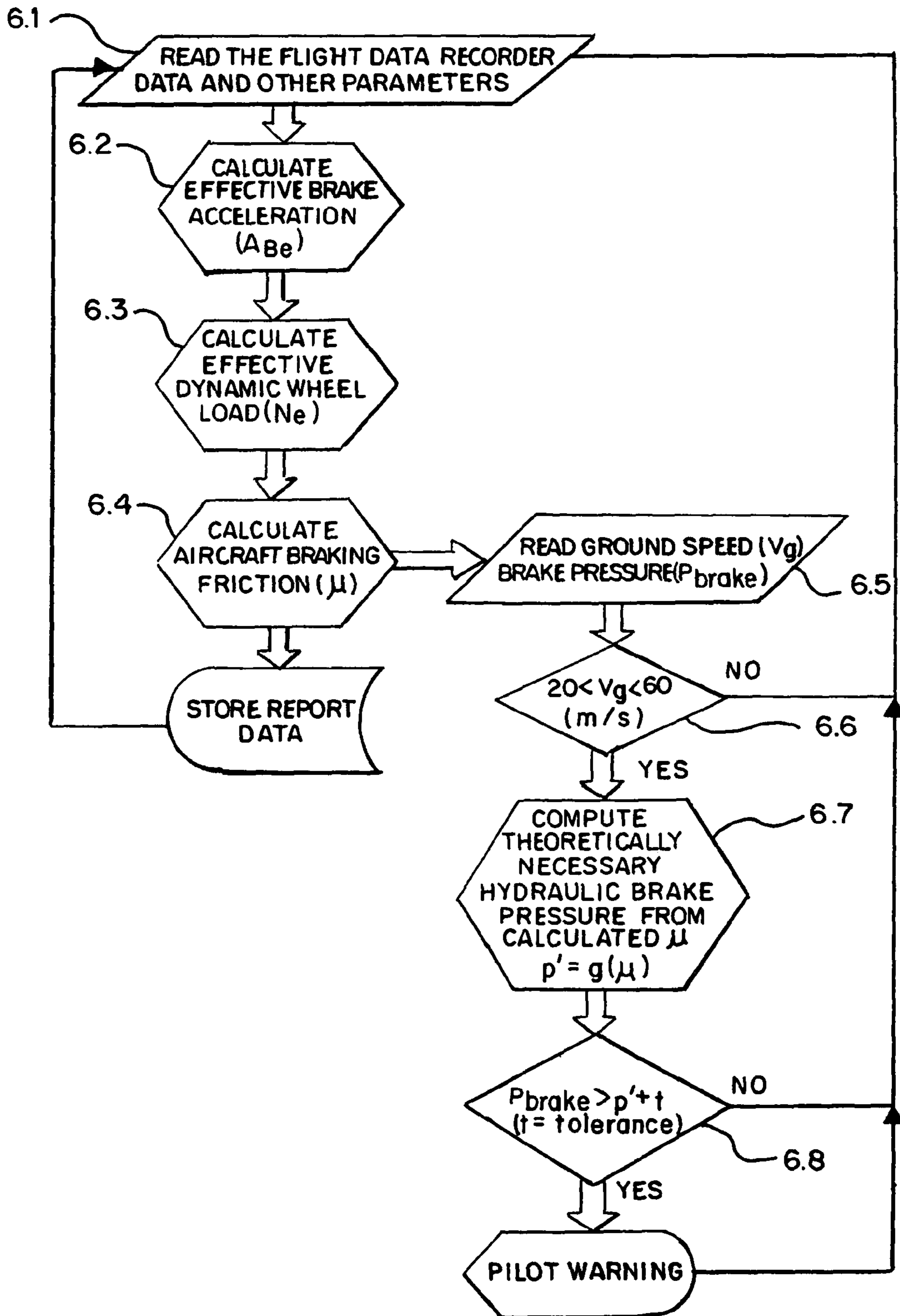
FIG. 5

A FRACTION OF EXAMPLE DATA FROM THE FLIGHT DATA RECORDER

PARAMETER	113	242	209	200	201	202	203	349	350	351	352	356	357
PARAMETER	JST	PRESSURE	CAS	AILERON	AILERON	AILERON	AILERON	AILERON	AILERON	AILERON	AILERON	AUTOBRAK	AUTOBRAK
ELAPSED TIME (SEC)	HR:MM:SS	ALTITUDE	LEFT	INBD	RIGHT	OUTBD	RIGHT	SENSOR	SENSOR	SENSOR	SENSOR	MODE	MODE
1		717	132	-6.9	-3.7		1.8	AIR	AIR	AIR	AIR	NOT	NOT
2	14:08:09	717	133.5	-3.5	-4.2	1.1		AIR	AIR	AIR	AIR	NOT	NOT
3		717	134	-4.6	-6		0.4	AIR	AIR	AIR	AIR	NOT	NOT
4		717	135.5	-3.3	-3.9	0.7		AIR	AIR	AIR	AIR	NOT	NOT
5		712	138.3	-7	-5.1		-0.4	AIR	AIR	AIR	AIR	NOT	NOT
6	14:08:13	705	141.3	-1.9	-3.2	0.7		AIR	AIR	AIR	AIR	NOT	NOT
7		693	142.5	-3.7	-3.7		1.9	AIR	AIR	AIR	AIR	NOT	NOT
8		678	143.8	-3.7	-4.4	1.1		AIR	AIR	AIR	AIR	NOT	NOT
9		667	141.5	-5.8	-1.4		3.2	AIR	AIR	AIR	AIR	NOT	NOT
10	14:08:17	653	140.8	-4.7	-2.8	0.5		AIR	AIR	AIR	AIR	NOT	NOT
11		637	141.5	-6.5	-3.5		1.8	AIR	AIR	AIR	AIR	NOT	NOT
12		622	139.5	-5.3	-3.7	0.9		AIR	AIR	AIR	AIR	NOT	NOT
13		612	138.3	-2.6	-6.3		0.4	AIR	AIR	AIR	AIR	NOT	NOT
14	14:08:21	603	140.8	-1.6	-7.6	3.3		AIR	AIR	AIR	AIR	NOT	NOT
15		589	138.8	-1.1	-7.2		-0.4	AIR	AIR	AIR	AIR	NOT	NOT
16		575	137.8	-3.7	-4.2	1.2		AIR	AIR	AIR	AIR	NOT	NOT
17		562	137.8	-3.5	-6.2		0.4	AIR	AIR	AIR	AIR	NOT	NOT
18	14:08:25	549	135.5	-1.6	-7.6	3.2		AIR	AIR	AIR	AIR	NOT	NOT
19		536	135.3	-4	-4.2		1.4	AIR	AIR	AIR	AIR	NOT	NOT
20		525	133	-3.3	-7.7	3.7		AIR	AIR	AIR	AIR	NOT	NOT
21		512	132.9	0.7	-8.6		-1.1	AIR	AIR	AIR	AIR	NOT	NOT
22	14:08:29	505	133	-2.1	-6.5	2.5		AIR	AIR	AIR	AIR	NOT	NOT
23		496	132	-3.2	-6.3		0.4	AIR	AIR	AIR	AIR	NOT	NOT
24		489	134.3	-1.9	-5.1	1.4		AIR	AIR	AIR	AIR	NOT	NOT
25		479	133.8	-6	-2.1		2.6	AIR	AIR	AIR	AIR	NOT	NOT
26	14:08:33	470	133.3	-6.5	-3.5	0.9		AIR	AIR	AIR	AIR	NOT	NOT
27		461	133.5	-1.9	-6.7		0.4	AIR	AIR	AIR	AIR	NOT	NOT
28		455	132.3	-3	-6.5	2.6		AIR	AIR	AIR	AIR	NOT	NOT

FIG. 6

THE METHOD OF THE CALCULATION



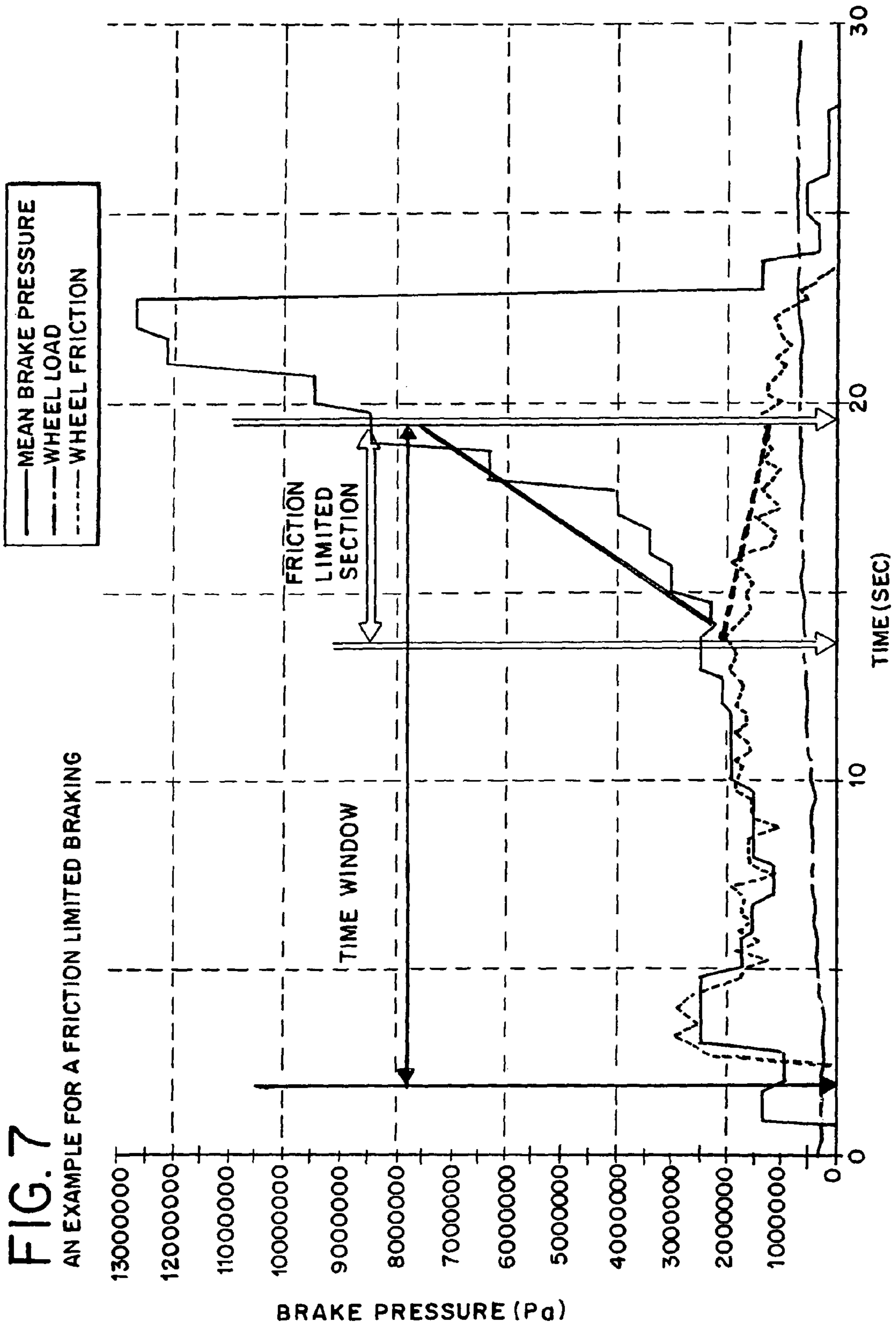


FIG. 8

POST PROCESSING AND DISTRIBUTION

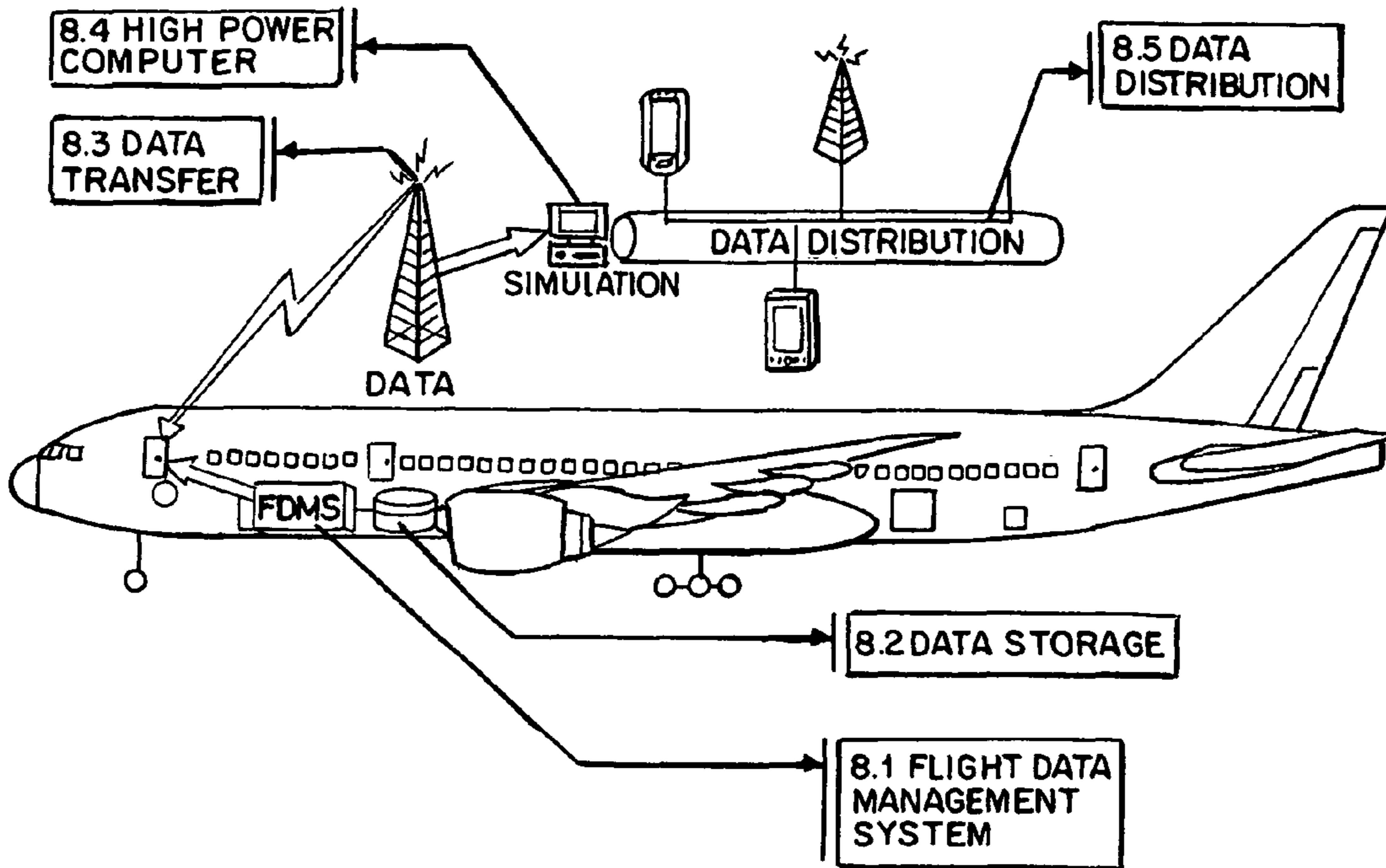
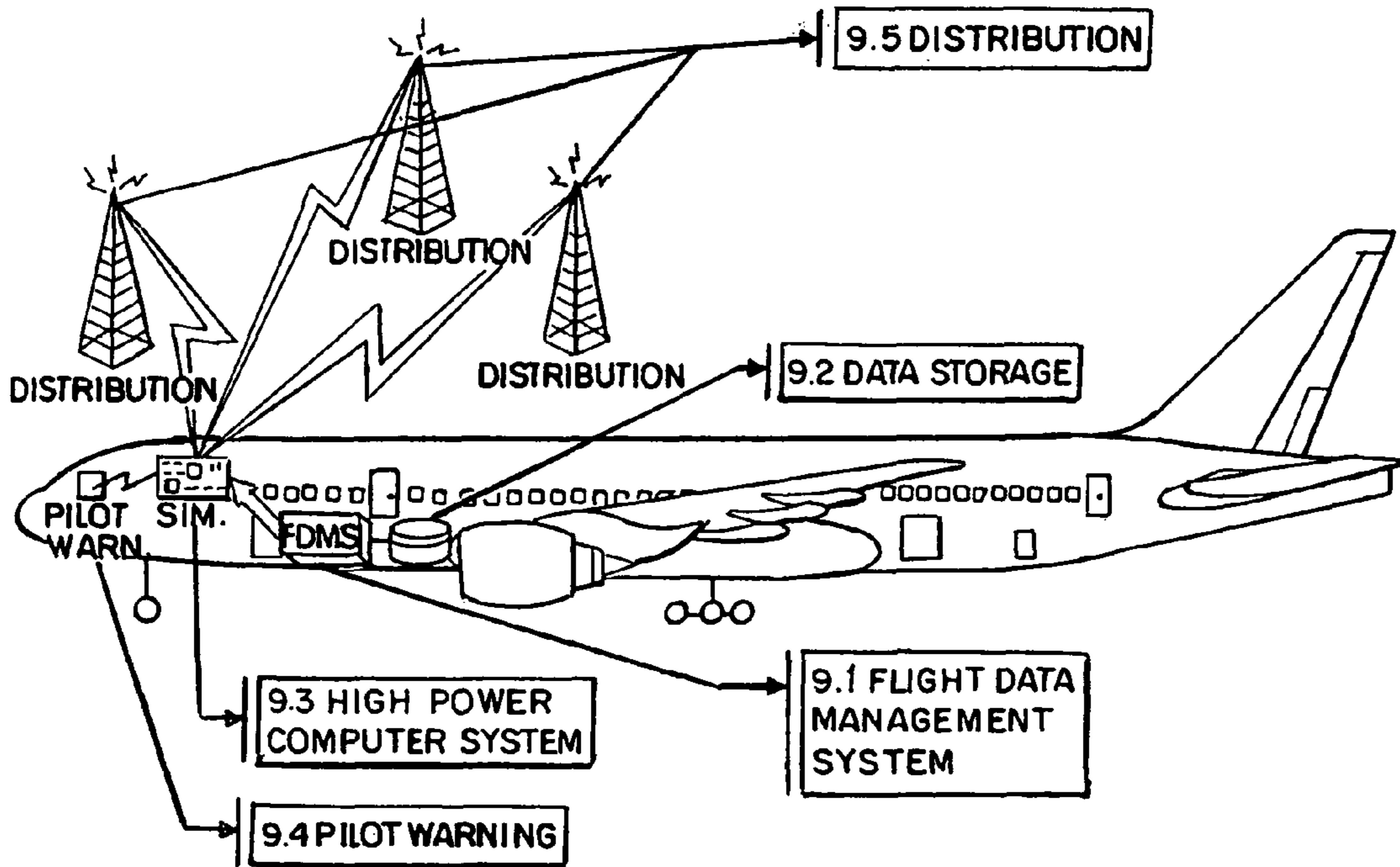


FIG. 9

REAL-TIME PROCESSING AND DISTRIBUTION



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**METHOD AND DEVICE OF CALCULATING
AIRCRAFT BRAKING FRICTION AND
OTHER RELATING LANDING
PERFORMANCE PARAMETERS BASED ON
THE DATA RECEIVED FROM AIRCRAFT'S
ON BOARD FLIGHT DATA MANAGEMENT
SYSTEM**

RELATED APPLICATION INFORMATION

This application is a continuation of U.S. application Ser. No. 13/374,757, filed Jan. 11, 2012, now U.S. Pat. No. 8,244,444 which, in turn, is a continuation of U.S. application Ser. No. 12/802,065, filed May 28, 2010, now U.S. Pat. No. 8,121,771, issued Feb. 21, 2012, which, in turn, is a continuation of U.S. application Ser. No. 11/352,984, filed Feb. 13, 2006, now U.S. Pat. No. 7,797,095, issued Sep. 14, 2010, which, in turn, claims the benefit of and priority from U.S. provisional application Ser. No. 60/654,914, filed Feb. 23, 2005, all of the disclosures of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of Invention

This invention relates to the method and the device of calculating aircraft braking friction and other aircraft performance and pavement surface characteristics parameters related to aircraft landing and takeoff including but not limited to aircraft braking action, aircraft takeoff distance, aircraft landing distance, runway surface conditions and runway surface friction—from now on referred to as true aircraft landing performance parameters—based on the data collected or otherwise available on board of an aircraft in electronic or other format from the aircraft Flight Data Recorder (FDR) or any other flight data providing or management system for example the Quick Access Recorder (QAR).

2. Background

Under severe winter conditions airlines, airports, civil aviation organizations and countries rigorously impose limits on aircraft takeoff, landing and other surface movement operations as well as enforce weight penalties for aircraft takeoffs and landings. These limits depend on the weather, runway and taxiway surface conditions and aircraft braking and takeoff performance. At the present these limits are calculated from the assumed aircraft braking performance based on runway conditions. These conditions are established by visual inspections, weather reports and the measurements of runway friction coefficient using ground friction measurement equipment.

At the present time, there are several practices to calculate the assumed aircraft braking performance:

1. The Canadian CRFI Method:

The CRFI method comprises a runway surface friction measurement performed by braking a passenger vehicle traveling on the runway at a certain speed and measuring the maximum deceleration of it at several locations along the length of the runway. The measured deceleration data is taken then and a braking index chart is used to calculate the assumed aircraft braking performance. The obtained aircraft landing performance data and calculated assumed braking friction is provided to airline operators, pilots and airport personnel for decision making.

2. The Reported Runway Friction Coefficient by a Runway Friction Measurement Equipment.

There are a great many number of runway friction measurement devices manufactured by different companies, in different countries and working based on different principles.

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Some of the most common devices are: (a) continuous friction measurement equipment (CFME); (b) decelerometers; and (c) side force friction coefficient measurement equipment. This equipment is operated by airport operation personnel according to the manufacturer's instructions on the runways, aprons, and taxiways and the measured friction coefficient is recorded. The recorded friction coefficient is then distributed to airline operation personnel, pilots, and airport personnel. The measured coefficient of friction is dependent on the measurement device. Under the same conditions and on the same runway different runway friction measurement devices based on different principles will record different runway friction coefficients. These runway friction coefficients are assumed to relate to actual aircraft landing and takeoff performance.

3. The New Proposed IRFI Method:

The International Runway Friction Index (IRFI) is a computational method to harmonize the reported runway friction numbers reported by the many different runway surface friction measurement equipments. The method was developed through an international effort with 14 participating countries. The method is a mathematical procedure based on simple linear correlations. The IRFI procedure is using a mathematical transformation to take the reported measurement of a runway friction measurement device and compute using simple mathematical methods an index called the IRFI. The mathematical procedures are the same for all the different runway friction measurement device using a different set of constant parameters that was determined for each individual device. It is assumed that using this procedure the different runway friction measurement devices reporting different friction coefficients can be harmonized. The calculated IRFI is assumed to correlate to aircraft landing and takeoff performance.

4. Pre-Determined Friction Levels Based on Observed Runway Conditions, Current and Forecasted Weather Conditions:

This method is available for airport operators according to new regulations. The method is based on airport personnel driving through the runway and personally observing the runway surface conditions. The ice, snow, water and other possible surface contaminants are visually observed and their depth measured or estimated by visual observation. The estimated runway conditions with weather information are then used to lookup runway friction coefficient in a table.

All these above mentioned practices are based on the measurement of the runway friction coefficient using ground friction measuring equipment, visual observation, weather information or combinations of these. However, according to present practices, there are several problems with the measurement of the runway friction coefficient using these methods.

1. Need of a Special Device/Car:

There is a special car needed to be able to measure the runway friction coefficient. There are special devices to measure the runway friction coefficient that are commercially available; however, most of these devices are very expensive. Therefore, not every airport can afford to have one.

2. Close of Runway:

For the duration of the measurement the runway has to be closed for takeoffs and landings as well as any aircraft movement. The measurement of the runway surface friction takes a relatively large amount of time since a measuring device has to travel the whole length of the runway at a minimum one time but during severe weather conditions it is possible that more than one measurement run is needed to determine runway surface friction. The closing of an active runway causes

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the suspension of takeoff and landing aircraft operations for a lengthened period of time and therefore is very costly for both the airlines and the airport. The use of ground vehicles to measure runway friction poses a safety hazard especially under severe weather conditions.

3. Inaccurate Result Due to Lack of Maintenance and Inaccurate Calibration Level:

The result of the measurements are very dependent of the maintenance and the calibration level of measurement devices, therefore the result can vary much, and could lose reliability.

4. Confusing Results Due to the Differences Between Ground Friction Devices:

It has been established that the frictional values reported by different types of ground friction measurement equipment are substantially different. In fact, the same type and manufacture, and even the same model of equipment frequently report highly scattered frictional data. Calibration and measurement procedures are different for different types of devices. The repeatability and reproducibility scatter, or in other words, uncertainty of measurements for each type of ground friction measurement device, is therefore amplified and the spread of friction measurement values among different equipment types is significant.

5. Inaccurate Result Due to Rapid Weather Change:

Airport operation personnel, in taking on the responsibility of conducting friction measurements during winter storms, find it difficult to keep up with the rapid changes in the weather. During winter storms runway surface conditions can change very quickly and therefore friction measurement results can become obsolete in a short amount of time, thus misrepresenting landing and takeoff conditions.

6. Inaccurate Result Due to the Difference Between Aircraft and the Ground Equipment:

It is proven that the aircraft braking friction coefficients of contaminated runways are different for aircrafts compared to those reported by the ground friction measurement equipment.

7. Inaccurate Result Due to the Lack of Uniform Runway Reporting Practices:

For many years the international aviation community has had no uniform runway friction reporting practices. The equipment used and procedures followed in taking friction measurements vary from country to country. Therefore, friction readings at various airports because of differences in reporting practices may not be reliable enough to calculate aircraft braking performance.

Therefore this invention recognizes the need for a system directly capable of determining the true aircraft landing performance parameters based on the data collected by and available in the aircraft Flight Data Recorder (FDR) or other flight data management systems. By utilizing the novel method in this invention, for the first time all involved personnel in the ground operations of an airport and airline operations including but not limited to aircraft pilots, airline operation officers and airline managers as well as airport operators, managers and maintenance crews, will have the most accurate and most recent information on runway surface friction and aircraft braking action, especially on winter contaminated and slippery runways.

Utilizing this method the aviation industry no longer has to rely on different friction reading from different instrumentations and from different procedures.

Therefore, this method will represent a direct and substantial benefit for the aviation industry.

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BRIEF SUMMARY OF THE INVENTION

Objective of Invention

The objective of this invention is to provide all personnel involved in the ground operations of an airport and involved in airline operations including but not limited to aircraft pilots, airline operation officers and airline managers as well as airport operators, managers and maintenance crews, the most accurate and most recent information on the true aircraft landing and takeoff performance parameters to help in a better and more accurate safety and economical decision making, and to prevent any accident, therefore save lives.

Brief Summary of the Invention

This unique and novel invention is based on the fact that most modern airplanes throughout the entire flight including the takeoff and landing measures, collects and stores data on all substantial aircraft systems including the braking hydraulics, speeds and hundreds of other performance parameters. During the landing maneuver real time or after the aircraft parked at the gate this data can be retrieved, processed and the true aircraft landing performance parameters can be calculated.

During a landing usually an aircraft uses its speed brakes, spoilers, flaps and hydraulic and mechanical braking system and other means to decelerate the aircraft to acceptable ground taxi speed. The performance of these systems together with many physical parameters including but not limited to various speeds, deceleration, temperatures, pressures, winds and other physical parameters are monitored, measured, collected and stored in a data management system on board of the aircraft (FIG. 1).

All monitored parameters can be fed real time into a high powered computer system that is capable of processing the data and calculating all relevant physical processes involved in the aircraft landing maneuver. Based upon the calculated physical processes the actual effective braking friction coefficient of the landing aircraft can be calculated. This, together with other parameters and weather data, can be used to calculate the true aircraft landing performance parameters (FIG. 6).

If real time data processing is not chosen, then the collected data from the aircraft can be transported by wired, wireless or any other means into a central processing unit where the same calculation can be performed (FIG. 8).

The obtained true aircraft landing performance parameters data then can be distributed to all involved personnel in the ground operations of an airport and airline operations including but not limited to aircraft pilots, airline operation officers and airline managers as well as airport operators, managers and maintenance crews.

Utilizing the novel method in this invention for the first time all personnel involved in the ground operations of an airport and airline operations including but not limited to aircraft pilots, airline operation officers and airline managers as well as airport operators, managers and maintenance crews, will have the most accurate and most recent information on runway surface friction and aircraft braking action.

Utilizing this method, all the above mentioned (see BACKGROUND OF THE INVENTION) problems can be solved:

1. No Need of a Special Device/Car:

This method uses the airplane itself as measuring equipment, therefore no additional equipment is needed. Moreover,

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no additional sensor is needed. This method uses the readings of present sensors and other readily available data of an aircraft.

2. No Need for Closing of Runway:

The duration of the measurement is the landing of the aircraft itself. Therefore the runway does not have to be closed.

3. No Inaccurate Result Due to Maintenance and the Calibration Level:

Because this method uses the aircraft itself as the measuring device, there is no variation due to the maintenance and the calibration level of these ground friction measuring devices. The result of the calculation will give back the exact aircraft braking friction the aircraft actually develops and encounters.

4. No Inaccurate Result Due to the Different Between Ground Friction Devices:

Because this method uses the aircraft itself as the measuring device, there is no variation due to the different ground friction measuring devices.

5. Accurate Result Even in Rapid Weather Change:

As long as aircraft are landing on the runway, the most accurate and most recent information on the true aircraft landing performance parameters will be provided by each landing.

6. No Inaccurate Result Due to the Difference Between Aircraft and the Ground Equipment:

Because this method uses the aircraft itself as the measuring device, there is no discrepancy in the measured and real friction due to the difference between aircraft and the ground equipment.

7. No Inaccurate Result Due to the Lack of Uniform Runway Reporting Practices:

Because this method uses the aircraft itself as the measuring device, there is no variation due to the difference in reporting practices.

Utilizing this method the aviation industry no longer has to rely on different friction readings from different instrumentations and from different procedures.

Therefore, this method represents a direct and substantial safety and economic benefits for the aviation industry.

The significance of this invention involves saving substantial amount of money for the airline industry by preventing over usage of critical parts and components of the aircraft, including but not limited to brakes, hydraulics, and engines.

While increasing the safety level of the takeoffs, it could generate substantial revenue for airlines by calculating the allowable take off weight, thus permissible cargo much more precisely.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic of a Flight Data Recorder illustrating the data collection structure of the Flight Data Recorder of an aircraft.

FIG. 2 is a table illustrating data available from the Flight Data Recorder of a landing aircraft to reflect Pressure Altitude (in feet) versus time during a landing of the aircraft.

FIG. 3 is a table illustrating data available from the Flight Data Recorder of a landing aircraft to reflect Brake Pressure (in pounds per square inch) versus Time during or landing of the aircraft.

FIG. 4 is a table illustrating data available from the Flight Data Recorder of a landing aircraft to reflect Autobrake Setting versus Time during landing of the aircraft.

FIG. 5 is a table illustrating a fraction of data available from a Flight Data Recorder.

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FIG. 6 is a schematic flow chart illustrating the method of determining various values generated by the present invention.

FIG. 7 is a table illustrating friction data indicative of limited braking plotting Mean Braking Pressure (in Pascals) versus Time (in Seconds) and illustrating corresponding Wheel Load and Wheel Friction.

FIG. 8 is a schematic illustrating transmission of data from a Flight Data Management System of a landing aircraft for post processing and distribution.

FIG. 9 is a schematic illustrating alternative real-time post processing and distribution and transmission of data from a Flight Data Management System of a landing aircraft.

DETAILED DESCRIPTION OF THE INVENTION

As illustrated in FIG. 1, this unique and novel invention is based on the fact that every airplane during landing uses the hydraulics and braking system. During a landing usually an aircraft uses its speed brakes, spoilers, flaps and hydraulic and mechanic braking system and other means to decelerate the aircraft to acceptable ground taxi speed. The performance of these systems together with many physical parameters including but not limited to various speeds, deceleration, temperatures, pressures, winds and other physical parameters are monitored, measured, collected and stored in a data management system on board of the aircraft. This figure presents the schematics of the three major components of data sources onboard of an aircraft relevant to this invention, the measured and recorded parameters related to the braking system, the measured and recorded parameters to the engines, flight and other control systems of the aircraft, and the dynamic, external and environmental parameters measured and recorded.

As illustrated in FIGS. 2 through 5, this invention uses the sequence of data points recorded from the touch down of the aircraft until it reaches the normal taxiing speed or comes to a stop. In the continuous data stream of the flight data management system the touch down is marked by several events making it possible to detect the beginning data point of the calculation process. From that point until the aircraft comes to complete stop at the gate every necessary data points can be identified within the recorded data. FIG. 2 shows the recorded altitude measurements for an actual landing FIG. 3 depicts the measured the recorded hydraulic braking pressures, FIG. 4 presents the recorded data for the auto-brake selection and FIG. 5 illustrate the format of the recorded data that can be obtained from a digital flight data management system.

As illustrated in FIG. 6, to arrive at the end result, a number of different mathematical and physical modeling approaches are possible through different sets of dynamic equations and/or various methods of simulations based upon the availability of different sets of data from the flight data management system.

The following equations only represent an example of the possible approaches, and therefore the invention and the presented method is not limited to these equations.

6.1—The following data is used as one of the possible minimum data sets for the calculation, although more and/or different data can be utilized to calculate the same parameters and/or improve the precision of the calculation.

Data from the Flight Data Recorder:

V_{air} —Air Speed,

P_{LB}, P_{RB} —Left and Right Brake Pressure,

V_g —Ground Speed,

A_x —Longitudinal Acceleration,

A_c —Vertical Acceleration,

E_{RPM} —Engine RPM,

$S_{spoiler}$ —Spoiler setting,
 $S_{airbrake}$ —Airbrake setting,
 $S_{aileron}$ —Aileron setting,
 C_{flap} —Flap configuration,
 θ_{pitch} —Pitch,
 S_{RT} —Reverse thrust setting,
 S_T —Engine thrust setting

The following environmental data are used in the calculation.

T_{air} —Air Temp,
 P_{alt} —Pressure Altitude,
 P_{air} —Air Pressure,
 $H\%$ —Relative humidity,
 Δ_{Runway} —Runway elevation

The following aircraft parameters are used in the calculation.

$M_{landing}$ —Landing Mass,
 E_{type} —Engine type,
 N_{engine} —Number of engines,
 TY_{tire} —Tire type,
 $TY_{aircraft}$ —Aircraft type

6.2—The method calculates, through a three-dimensional dynamic model, all relevant physical processes involved in the aircraft landing maneuver and separates them so they are individually available for use. The first intermediate result of the method is the time or distance history of all relevant, separated, interdependent decelerations generated by the different systems in an aircraft. These decelerations are cumulatively measured by the onboard measurement system and reported in the flight data stream. The separated decelerations calculated from the different physical processes make it possible to calculate the true deceleration developed only by the actual effective braking friction coefficient of the landing aircraft.

Based on the above, the software calculates the brake effective acceleration vs. time based on Equation (1).

$$A_{Be} = A_x - A_{Drag} - A_{ReverseThrust} - A_{RollingResistance} - A_{Pitch} \quad (1)$$

where A_{Be} is the brake effective acceleration

A_x is the measured cumulative longitudinal acceleration (6.1)

A_{Drag} is the deceleration due to the aerodynamic drag,

$$A_{Drag} = f(V_{air}, S_{spoiler}, S_{airbrake}, S_{aileron}, C_{flap}, T_{air}, P_{air}, H_{\%}, M_{landing}, TY_{aircraft}) \quad (2)$$

where V_{air} , $S_{spoiler}$, $S_{airbrake}$, $S_{aileron}$, C_{flap} , T_{air} , P_{air} , $H_{\%}$, $M_{landing}$, $TY_{aircraft}$ are parameters from 6.1.

$A_{ReverseThrust}$ is the acceleration caused by thrust/reverse-thrust

$$A_{ReverseThrust} = f(E_{type}, N_{engine}, T_{air}, P_{air}, H_{\%}, E_{RPM}, S_{RT}, M_{landing}, TY_{aircraft}) \quad (3)$$

where E_{type} , N_{engine} , T_{air} , P_{air} , $H_{\%}$, E_{RPM} , S_{RT} , $M_{landing}$, $TY_{aircraft}$ are parameters from 6.1

$A_{RollingResistance}$ is the cumulative deceleration due to other effects such as tire rolling resistance, runway longitudinal elevation

$$A_{RollingResistance} = f(tire, V_g, M_{landing}) \quad (4)$$

where $tire$, V_g , $M_{landing}$ are parameters from 6.1

A_{Pitch} is due to the runway elevation

$$A_{Pitch} = f(\Delta_{Runway}) \quad (5)$$

where Δ_{Runway} is the runway elevation from 6.1.

This true deceleration (A_{Be}) developed only by the actual effective braking friction coefficient of the landing aircraft, then can be used in further calculations to determine the true aircraft braking coefficient of friction.

6.3—Using the recorded data stream of the aircraft with the parameters indicated in point 6.1, plus weather and environmental factors reported by the airport or measured onboard of the aircraft and therefore available in the recorded data, together with known performance and design parameters of the aircraft available from design documentation and in the literature, the dynamic model calculates all relevant actual forces acting on the aircraft as a function of the true ground and air speeds, travel distance and time. Using the results, the dynamic wheel loads of all main gears and the nose gear can be calculated.

Since the dynamic vertical acceleration of the aircraft is measured by the onboard inertial instrumentation, the effective dynamic wheel load (N) can be calculated by the deduction of the calculated retarding forces by means of known aircraft mass; together with the determined gravitational measurement biases introduced by runway geometry and aircraft physics using Equations 6 through 9.

$$N = M_{Landing} \cdot \cos(\theta_{pitch}) \cdot g - \text{Lift} - \text{LoadTransfer} - \text{MomentumLift} + g(A_c, M_{Landing}) \quad (6)$$

Where

Lift is the computed force of the sum of all lifting forces acting on the aircraft through aerodynamics:

$$\text{Lift} = f(V_{air}, S_{spoiler}, S_{airbrake}, S_{aileron}, C_{flap}, T_{air}, P_{air}, H_{\%}, M_{landing}, TY_{aircraft}) \quad (7)$$

where V_{air} , $S_{spoiler}$, $S_{airbrake}$, $S_{aileron}$, C_{flap} , T_{air} , P_{air} , $H_{\%}$, $M_{landing}$, $TY_{aircraft}$ are parameters from point 6.1. LoadTransfer is the load transfer from the main landing gear to the nose gear due to the deceleration of the aircraft:

$$\text{LoadTransfer} = f(A_{Be}, M_{landing}, TY_{aircraft}) \quad (8)$$

where A_{Be} , $M_{landing}$, $TY_{aircraft}$ are parameters from 6.1. MomentumLift is the generated loading or lifting forces produced by moments acting on the aircraft body due to the acting points of lift, thrust and reverse-thrust forces on the aircraft geometry:

$$\text{MomentumLift} = f(S_{Thrust}, S_{RT}, C_{flap}, TY_{aircraft}) \quad (9)$$

where S_{Thrust} , S_{RT} , C_{flap} , $TY_{aircraft}$ are parameters from point 6.1

$g(A_c, M_{landing})$ is the dynamic force acting on the landing gear due to the dynamic vertical movement of the aircraft, and thus the varying load on the main gear due to the runway roughness,

where A_c , $M_{landing}$ are parameters from point 6.1.

6.4—The deceleration caused by the wheel braking system of the aircraft calculated in point 6.2 (A_{Be} is the true brake effective deceleration), together with the computed actual wheel load forces acting on the main gears of the aircraft can be used to calculate the true braking coefficient of friction. First the actual true deceleration force or friction force (F_{Fr}) caused by the effective braking of the aircraft have to be computed. From the brake effective deceleration (A_{Be}) obtained in 6.2 and the available aircraft mass, the method calculates the true effective friction force based on the formula:

$$F_{Fr} = M_{Landing} \cdot A_{Be} \quad (10)$$

where

$M_{Landing}$ is the landing mass of the aircraft from point 6.1 and

A_{Be} is the calculated brake effective deceleration from Equation (1).

The determined true deceleration force (F_{Fr}) in equation 10 together with the actual effective dynamic wheel load (N)

obtained in 6.3 can be utilized to calculate the true effective braking coefficient of friction μ using equation 11:

$$\mu = F_{Fr} / N \quad (11)$$

where

N is the calculated effective dynamic wheel force acting on the tire (6.3),

and F_{Fr} is the friction force from Equation (10).

6.5—Using the calculated effective true frictional forces, together with parameters measured by the aircraft data management system (such as downstream hydraulic braking pressure), a logical algorithm based on the physics of the braking of pneumatic tires with antiskid braking systems was designed to determine whether the maximum available runway friction was reached within the relevant speed ranges of the landing maneuver.

Together with the actual friction force the following logic is used by this invention to determine:

(A) If friction limited braking is encountered—If the actual available maximum braking friction available for the aircraft was reached by the braking system and even though more retardation was needed the braking system could not generate because of the insufficient amount of runway surface friction a friction limited braking was encountered.

(B) If adequate friction for the braking maneuver was available—If friction limited braking was not encountered and the braking was limited by manual braking or the preset level of the auto-brake system, the adequate surface friction and actual friction coefficient can be calculated and verified.

6.6—In order to make sure that the auto-brake and antiskid systems of the aircraft were working in their operational range, the algorithm analyzes the data to look for the friction limited sections only in an operational window where the landing speed is between 20 m/s and 60 m/s.

6.7—From the computed true effective braking coefficient of friction μ calculated in 6.4, the method computes the theoretically necessary hydraulic brake pressure P_{brake} and from the dynamics of the landing parameters an applicable tolerance is calculated t.

6.8—The data is analyzed for the deviation of the applied downstream hydraulic brake pressure from the calculated theoretical brake pressure from 6.7 according to the obtained effective braking friction within the allowed operational window by the determined t tolerance. A sharp deviation of the achieved and the calculated hydraulic braking pressure is the indication of friction limited braking. When sharply increased hydraulic pressure is applied by the braking system, while no significant friction increase is generated, the potential of true friction limited braking occurs.

FIG. 7 illustrates a graphical presentation for an example for the friction limited braking, where it can be seen that that a sharply increasing hydraulic pressure is applied by the braking system, while the friction is decreasing. This is a very good example for a true friction limited braking.

The Different Applications of this Method
The Post Processing

FIG. 8 illustrates one possible approach in obtaining the true aircraft landing performance parameters is a method of post processing. The data from the aircraft flight data management system is retrieved not real time but only after the aircraft is finished its landing, taxiing and other ground maneuvers and arrived at its final ground position. The schematic of this approach is described in FIG. 8.

8.1—All monitored and available data is sent to the flight data management system throughout the aircraft landing and ground maneuver.

8.2—The Flight Data Management system collects, processes and stores the retrieved data in a data storage. The data storage is in fact part of the Flight Data Management system where all the data is stored.

8.3—Data transfer—After the airplane stopped at the gate or other designated final position, the collected data from the aircraft can be transported by wired, wireless or other means into a central processing unit.

8.4—High Power computer—All recorded parameters transported from the aircraft can be fed into a computer system, which is capable of processing the data and calculating/simulating all relevant physical processes involved in the aircraft landing maneuver and the actual effective braking friction coefficient of the landing aircraft and the true aircraft landing performance parameters can be computed and made ready for distribution.

8.5—Data Distribution—The computer distributes the calculated true landing parameters to other interested parties through wired, wireless or other data transportation means.

Real-Time Data Processing

As illustrated in FIG. 9, in the case of real time data processing, all monitored parameters can be fed real time into an onboard high power computer system that is capable of processing the data and calculating all relevant physical processes involved in the aircraft landing maneuver. Based upon the calculated physical processes the actual effective braking friction coefficient of the landing aircraft can be calculated. This together with other parameters and weather data can be used to calculate the true aircraft landing performance parameters. In case the calculation finds a true friction limited section, a warning can be sent to the pilot to prevent any accident, such as over run or slide off the runway.

9.1—All monitored and available data is sent to the flight data management system throughout the aircraft landing and ground maneuver.

9.2—The Flight Data Management system collects, processes and stores the retrieved data in a data storage. The data storage is in fact part of the Flight Data Management system where all the data is stored.

9.3—High power computer system: All monitored parameters are fed real time into a computer system, which is capable of processing the data and calculating/simulating all relevant physical processes involved in the aircraft landing maneuver and the actual effective braking friction coefficient of the landing aircraft and the true aircraft landing performance parameters.

9.4—Pilot warning: Based on the calculated aircraft braking coefficient and the method to search for friction limited braking it gives a warning in case the friction is too low or continuously informs the driver of the generated and available braking and cornering coefficient of friction.

9.5—Distribution: The onboard computer distributes the calculated true landing parameters to other interested parties.

Significance of the Invention

Utilizing the novel method in this invention for the first time all personnel involved in the ground operations of an airport as well as airline personnel involved in operations including but not limited to aircraft pilots, airline operation officers and airline managers as well as airport operators, managers and maintenance crews, will have the most accurate and most recent information on runway surface friction and aircraft braking action.

Utilizing this method the aviation industry no longer has to rely on different friction readings from different instrumentations and from different procedures or assumed friction levels based on visual observation and weather data.

Therefore, this method represents a direct and substantial safety and economic benefits for the aviation industry.

Economic Benefits

The significance of this invention involves knowing the true aircraft landing performance parameters for landing which yields substantial financial savings for the airline industry. While increasing the safety level of the takeoffs, it could also generate substantial revenue for airlines.

Therefore a system directly capable of determining the true aircraft landing performance parameters would represent direct and substantial economic benefit for the aviation industry including but not limited to:

1. Preventing over usage of critical parts, components of the aircraft including but not limited to brakes, hydraulics, and engines.
2. The distribution of the calculated parameters for the airport management helps make more accurate, timely and economic decisions including but not limited to decision on closing the airport or decision on the necessary maintenance.
3. The calculated parameters reported to the airline management yields more accurate and economic decision making including but not limited to permitting the calculation of allowable take off weights much more precisely thus increasing the permissible cargo limits.

Safety Benefits

The significance of this invention involves the precise assessment of the true runway surface characteristics and aircraft braking and landing performance by providing the true aircraft landing performance parameters. This is fundamental to airport aviation safety, and economical operations especially under winter conditions and slippery runways. Thus, a system directly capable of determining the true aircraft landing performance parameters real-time and under any conditions without restricting ground operations of an airport would represent direct and substantial safety benefit for the aviation industry including but not limited to:

1. Providing real-time low friction warning to help pilots to make critical decisions during landing or take-off operations to prevent accidents, costly damages or loss of human lives.
2. Eliminating the confusion in the interpretation of the different Ground Friction Measuring Device readings and therefore giving precise data to airport personnel for critical and economical decision making in airport operations and maintenance.
3. Giving an accurate assessment of the actual surface conditions of the runway, that could be used in the aircraft cargo's loading decision making for safer landing or take-offs.
4. Providing accurate data for distribution to airport management personnel assisting them in more accurate, timely and safe decision making.
5. Providing data to be reported to pilots about to land for safer and more accurate landing preparation.
6. Providing data to be reported to pilots about to take off for safer and more accurate takeoff preparation.
7. It could be reported to the airline management to for more accurate safety decision making.

I claim:

1. A computer network for calculating and distributing a true aircraft friction braking friction coefficient for an aircraft landing surface comprising:

- (A) A computer that communicates with a flight data management system of a landing aircraft that is landing or has landed on the aircraft landing surface, wherein the aircraft's flight data management system has recorded

thereon one or more sets of data points relating to one or more of the landing aircraft's following aircraft performance properties over a period of time: aircraft ground speed, aircraft brake pressure, aircraft longitudinal acceleration, aircraft engine thrust setting, aircraft reverse thrust setting, aircraft engine revolutions per minute, aircraft air speed, aircraft vertical acceleration, aircraft spoiler setting, aircraft airbrake setting, aircraft aileron setting, aircraft flap configuration, aircraft pitch, and aircraft autobrake setting;

(B) Wherein the computer communicates with the landing aircraft's flight data management system and obtains from the landing aircraft's flight data management system the one or more sets of the aircraft performance property data points recorded on the landing aircraft's flight data management system;

(C) Wherein the computer communicates with one or more environmental data sources, wherein the one or more environmental data sources have recorded thereon one or more sets of data points relating to one or more environmental parameters, the data points relating to the one or more environmental parameters being chosen from the following group: air temperature, air pressure, relative humidity, wind speed, wind direction, pressure altitude, and aircraft landing surface elevation;

(D) Wherein the computer communicates with the one or more environmental data sources and obtains the one or more sets of data points relating to the one or more environmental parameters;

(E) Wherein the computer is capable of communicating with one or more aircraft data sources, wherein the one or more aircraft data sources have recorded thereon one or more sets of data points relating to aircraft parameters pertaining to the landing aircraft, and wherein the computer obtains from the one or more aircraft data sources the one or more sets of the data points relating to aircraft parameters pertaining to the landing aircraft, being chosen from the following group: aircraft landing mass, aircraft engine type, number of aircraft engines, aircraft tire type, and aircraft type;

(F) Wherein the computer communicates with the one or more aircraft data sources and obtains the one or more sets of data points relating to the one or more aircraft parameters pertaining to the landing aircraft;

(G) Wherein the computer calculates the true aircraft braking friction coefficient of the aircraft landing surface: (i) using at least one of the one or more sets of the aircraft performance property data points obtained by the computer from the landing aircraft's flight data management system; (ii) using at least one of the one or more sets of the data points obtained by the computer from the one or more environmental data sources; and (iii) using at least one of the one or more sets of the data points obtained by the computer from the one or more aircraft data sources.

2. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 1 wherein the one or more sets of data points relating to one or more environmental parameters are measured substantially proximate to the time that the landing aircraft touched down on the aircraft landing surface.

3. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 1 wherein the one or more sets of data points relating to one or more environmental parameters are measured between substantially the point in time that the landing aircraft touched down on the landing surface and a first predetermined point in time thereafter.

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4. The computer network for calculating and distributing the true aircraft braking coefficient of the landing surface of claim 1 wherein the aircraft performance property data points obtained directly or indirectly from the landing aircraft's flight data management system comprise data points pertaining to the landing aircraft's performance properties between substantially a point in time that the landing aircraft touched down on the aircraft landing surface and a first predetermined point in time thereafter.

5. The computer network for calculating and distributing the true aircraft braking coefficient of the landing surface of claim 2 wherein the aircraft performance property data points obtained directly or indirectly from the landing aircraft's flight data management system comprise data points pertaining to the landing aircraft's performance properties between substantially a point in time that the landing aircraft touched down on the aircraft landing surface and a first predetermined point in time thereafter.

6. The computer network for calculating and distributing the true aircraft braking coefficient of the landing surface of claim 4 wherein the computer communicates with the landing aircraft's flight data management system between substantially the point in time that the landing aircraft touched down on the aircraft landing surface and a second predetermined point in time thereafter, and obtains directly or indirectly from the flight data management system the one or more sets of aircraft performance property data points, wherein the second predetermined point in time may be substantially the same as or substantially different from the first predetermined point in time.

7. The computer network for calculating and distributing the true aircraft braking coefficient of the landing surface of claim 5 wherein the computer communicates with the landing aircraft's flight data management system between substantially the point in time that the landing aircraft touched down on the aircraft landing surface and a second predetermined point in time thereafter, and obtains directly or indirectly from the flight data management system the one or more sets of aircraft performance property data points, wherein the second predetermined point in time may be substantially the same as or substantially different from the first predetermined point in time.

8. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 4 wherein the landing aircraft's flight data management system comprises a flight data recorder.

9. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 6 wherein the landing aircraft's flight data management system comprises a flight data recorder.

10. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 4 wherein the landing aircraft's flight data management system comprises a quick access recorder.

11. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 6 wherein the landing aircraft's flight data management system comprises a quick access recorder.

12. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 1 wherein the one or more sets of the aircraft performance property data points obtained from the landing aircraft's flight data management system are obtained by the computer directly or indirectly from the landing aircraft's flight data management system.

13. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft

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landing surface of claim 1 wherein the one or more sets of the aircraft performance property data points are obtained by the computer directly or indirectly from the landing aircraft's flight data management system after the landing aircraft stops.

14. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 4 wherein the first predetermined point in time is after the landing aircraft substantially reaches taxi speed.

15. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 4 wherein the first predetermined point in time is after the landing aircraft stops.

16. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 1 wherein at least one of the one or more environmental data sources comprises the landing aircraft's flight data management system, wherein at least one of the one or more sets of the data points relating to the one or more environmental parameters are measured by instrumentation on the landing aircraft and are recorded on the landing aircraft's flight data management system, and wherein at least one of the one or more sets of the data points relating to the one or more environmental parameters are obtained from the landing aircraft's flight data management system by the computer.

17. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 1 wherein at least one of the one or more aircraft data sources comprises a computer database, wherein at least one of the one or more sets of the data points relating to the one or more aircraft parameters relating to the landing aircraft are recorded on the computer database, and wherein at least one of the one or more sets of the data points relating to aircraft parameters pertaining to the landing aircraft are obtained from the computer database by the computer.

18. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 1 wherein at least one of the one or more aircraft data sources comprises the landing aircraft's flight data management system, wherein at least one of the one or more sets of the data points relating to the one or more aircraft parameters relating to the landing aircraft are recorded on the landing aircraft's flight data management system, and wherein at least one of the one or more sets of the data points relating to the one or more aircraft parameters are obtained from the landing aircraft's flight data management system by the computer.

19. The computer network for calculating and distributing the true aircraft braking friction coefficient of the aircraft landing surface of claim 1 wherein the aircraft braking friction coefficient calculated by the computer is distributed by the computer to one or more predetermined computer output recipients.

20. The computer network for calculating and distributing the true aircraft braking friction coefficient for the aircraft landing surface of claim 19 wherein the one or more predetermined computer output recipients to whom the true aircraft braking coefficient of the aircraft landing surface calculated by the computer are distributed are chosen from one or more of the following groups: airline operation personnel, pilots, airport personnel, airline managers, airport managers, airport maintenance crews, pilots of aircraft scheduled to take off or land on the aircraft landing surface, personnel involved in ground operations where the aircraft landing surface is

located, aircraft scheduling and dispatch personnel, flight service center personnel, government aviation authority personnel, air traffic controllers, airline employees, and aircraft manufacturers.

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